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STEADY-STATE CHARACTERISTICS OF A VOLTAGE REGULATOR AND A PARASITIC SPEED CONTROLLER ON A 14.3-KILOVOLT-AMPERE, 1200-HERTZ MODIFIED LUNDELL ALTERNATOR

by Bill D. Ingle, Heinz L. Wimmer, and Richard C. Bainbridge

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

The prototype control components of a 10-kW, 1200-Hz Brayton electrical subsystem were tested utilizing a prototype Brayton (research) alternator. These tests were performed to obtain preliminary data prior to the operation of the integrated Brayton system. The control components consist of an electronic voltage regulator and a parasitic-loading speed controller. The steady-state results of the test program are presented herein. These results verify the capability of the electrical components to deliver full rated load at the desired levels of voltage and frequency.

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SUMMARY

The prototype control components of a 10-kilowatt, 1200-hertz Brayton electrical subsystem were tested utilizing a prototype Brayton (research) alternator. The tests involving these components were performed to obtain preliminary data prior to the operation of the integrated Brayton system. The integrated Brayton system is one of a series of power generating systems which have been or are being investigated by this center. These systems are being developed for application in space environments.

The control components consist of an electronic voltage regulator and a parasitic-loading speed controller. The controls were packaged for operation in a vacuum environment. The tests reported herein were performed at atmospheric pressure. The test pressure which was used was selected for convenience only. The test program for the electrical subsystem included steady-state and transient testing. The steady-state characteristics of the subsystem utilizing the prototype components is presented herein. The transient characteristics are reported separately. The results of the test program verify the capability of the electrical components to deliver full rated load at the desired levels of voltage and frequency. The frequency control range which was obtained in this test program was 1200 hertz, plus 2 percent, minus zero for a useful load range of 10 kilowatts. The rms line voltage variation which was obtained in this test program was 120 volts (line to neutral), plus 3.2 volts, minus 2.0 volts over the range of useful load. A 3-volt change in line voltage which resulted from an interaction between control components is included in this voltage variation.

INTRODUCTION

A 10-kilowatt, 1200-hertz Brayton-cycle electrical generating system capable of operating in space environments is under development at the Lewis Research Center (ref. 1). This Brayton system is one of a series of power generating systems (refs. 2 and 3) which either have been or are being investigated by this center as part of a program to develop power systems for space application.

The 1200-hertz Brayton system includes a single-shaft turbine-alternator-compressor energy conversion system having a working gas consisting of a mixture of helium and xenon with a molecular weight of approximately 83.8 and a pressure of approximately 40 psia (2.76×10^5 N/m^2). As a part of this Brayton program, the control components of the electrical subsystem (the voltage regulator and the parasitic speed controller) were packaged for operation in a vacuum environment. The electrical control package (ECP), together with a prototype Brayton (research) alternator, was installed in a Lewis test facility for the purpose of obtaining performance data prior to the operation of the integrated Brayton system. The parasitic type of speed control as applied to the 1200-hertz Brayton system has also been applied to the SNAP-8 (ref. 2), 400-hertz Brayton (ref. 3), Sunflower (ref. 4), and SNAP-2 (ref. 5) power systems.

The steady-state performance characteristics of the electrical subsystem, which utilizes the prototype components mentioned previously, are presented herein. Some of the pertinent voltage and current waveshapes generated within the test system are reviewed for various levels of vehicle load.

The steady-state performance goals for the electrical subsystem, as reported herein, are summarized in table I.

The test program for this electrical subsystem included transient testing in addition to steady state. The test results related to the transient aspects of this program are reported separately (ref. 6).

TABLE I. - STEADY-STATE

PERFORMANCE GOALS

Voltage:	
Rated, V	120/208
Regulation, percent	±1
Modulation,[a] percent	1/2
Operating range, V	80 to 120
Frequency:	
Rated, Hz	1200
Regulation, percent	±1
Operating range, Hz	600 to 1800

[a]Alternator - voltage regulator combination only.

DESCRIPTION OF BRAYTON ELECTRICAL COMPONENTS

A discussion of each of the electrical prototype components is presented in this section. This discussion covers the principles of operation of the individual circuits as well as the performance characteristics of these circuits. The performance data were recorded during open-loop tests which were conducted at the NASA Lewis Research Center. A considerable part of this component discussion has been reported previously (refs. 7 and 8). The information contained in this component section is not essential to the comprehension of the section RESULTS AND DISCUSSION which follows later in this report.

The electrical subsystem, as illustrated in figure 1, consists of a turbine-driven

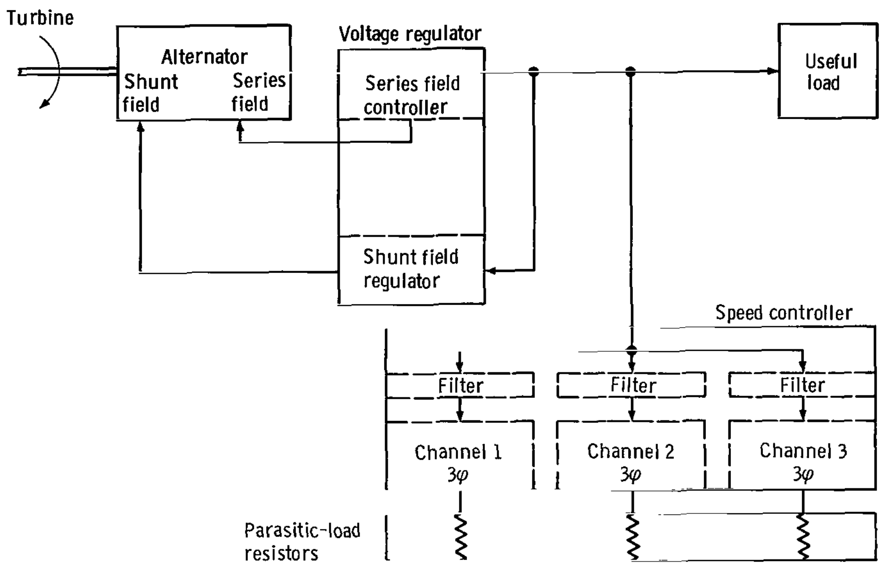


Figure 1. - Block diagram of Brayton electrical system.

alternator and an electronic solid-state voltage regulator and speed (frequency) controller (ref. 7). The alternator design includes two separate fields. One field is excited as a function of the level of the line voltage. This excitation is supplied by the shunt field regulator to provide subsystem voltage regulation. The second alternator field is excited in proportion to the level of line current. This excitation is supplied by the series field controller to provide load and fault compensation. An inductor-capacitor (LC) filter network is connected to the input of the speed controller. The purpose of the filter is to reduce the noise level at the alternator output that is generated by the speed controller.

The speed control function is accomplished by the use of multiple parasitic-loading controllers (see fig. 1). Multiple controllers are utilized to reduce the level of voltage distortion (ref. 9) present at the useful-load power bus. The voltage distortion is produced to a large extent by the speed controllers. The subject of voltage distortion receives further attention in the section Speed Controller.

Functionally, the parasitic-loading speed controller maintains a balance between the turbine power developed and the total alternator load. This balance is accomplished by applying parasitic load, as needed, to compensate for changes in useful load. The useful load plus parasitic (including losses) must equal the turbine power developed.

Alternator

The alternator design is based on the principle of the Lundell alternator and has a design rating of 14.3 kilovolt-amperes and 0.75 (lagging) power factor (PF) at an efficiency of 90.3 percent (ref. 10). The alternator rotor has a smooth cylindrical surface consisting of four poles and operates at 36 000 rpm. The research alternator used in the tests reported herein operated on oil-mist-lubricated bearings. The bearings in the turbine-alternator-compressor assembly for the integrated Brayton system operates on gas-lubricated bearings.

The stator of the alternator includes the two field windings and the armature winding. The armature winding has four parallel circuits to minimize the forces produced by magnetic unbalances. The alternator field power requirement is 62 watts (total) at the alternator design rating (14.3 kVA, 0.75 PF lagging, and 1200 Hz) of which approximately 45 percent, or 28 watts, is dissipated in the shunt field (ref. 8).

Shunt Field Regulator

Functionally, the shunt field regulator, as illustrated in the block diagram of figure 2, senses the level of the alternator line voltage. For voltage values below a predetermined level, the regulator turns on (the output power amplifier is saturated). For higher values of voltage, the regulator turns off.

The output (field) voltage is pulse-width modulated. The output is converted to a unidirectional current by the use of a free-wheeling diode. The regulator includes a current-limit function for the protection of the alternator field. The major subcircuits within the regulator are a voltage sensor, a voltage reference, a comparator, an amplifier, a power amplifier (output), and a current limiter, as shown in figure 2. The regulator utilizes transistors operating in a switching mode (ref. 8).

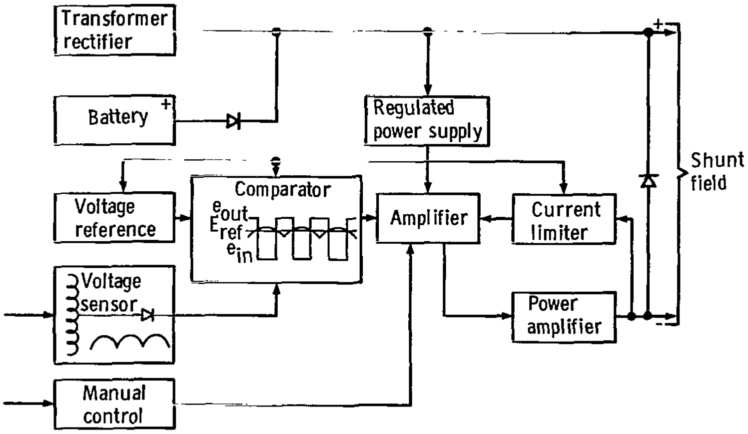


Figure 2. - Block diagram of shunt regulator.

The system voltage adjustment is accomplished by attenuating the voltage output of the sensing circuit. A capacitor in the sensor forces the shunt field regulator output to synchronize its turnon and turnoff with the ripple of the rectified sensing voltage. The switching frequency of the regulator is nominally 3600 hertz. The output of the voltage sensor and the voltage reference are compared in a differential amplifier, which is referred to as the comparator circuit. The reference signal is 6.3 volts dc. The output of the comparator circuit is amplified and applied to the power amplifier. The power amplifier consists of a driver transistor and an output transistor which supplies the shunt field excitation.

The field current limiter senses the current in the power amplifier output transistor. An adjustable percentage of this limit signal is compared with a reference signal. The shunt field current is limited by overriding the comparator circuit signal. The limiter restricts the field current to a value generally not exceeding 5 amperes. The maximum output voltage of the shunt field regulator is 42 volts. The power losses in the regulator are 41 watts at rated output with an efficiency of approximately 40 percent.

In figure 3, the control characteristic of the shunt field regulator is shown. The figure illustrates the buildup of the output voltage, the current limiting action (as previously discussed), and the normal regulation range. The regulator power amplifier output transistor is saturated between points A and B. Therefore, the slope of the curve is a function of line voltage, field resistance, and the voltage transformation ratio within the regulator. Point A indicates the minimum line voltage (~7 V) required to saturate the power amplifier output transistor. At point B (~80 V), the current limiter turns on. The regulator output is cycled on and off at a rate determined by a resistor-capacitor (RC) network within the limiter circuit. At point C (~118 V), the output of the voltage sensor circuit begins to control the amplifier, which, in turn, reduces the on state of

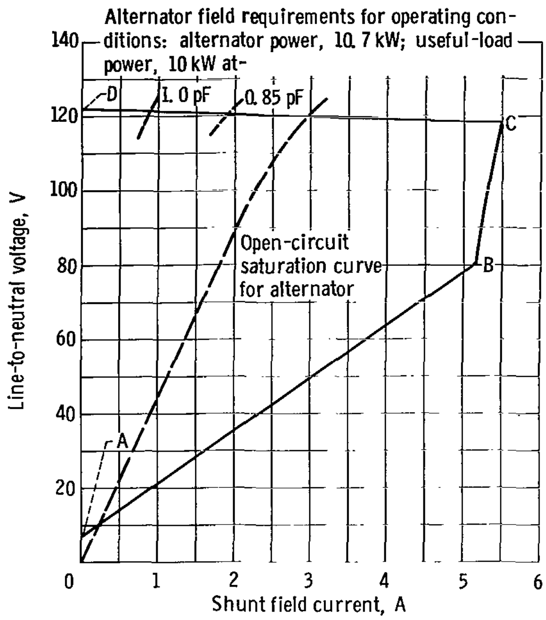


Figure 3. - Shunt field regulator control characteristic. Resistance shunt field, 4.0 ohms at 177° C.

the regulator. At higher values of line voltage, the regulator output goes to a full-off state, as illustrated at point D.

Superimposed on the regulator characteristic curve of figure 3 are the alternator field requirements for various operating conditions (dashed curves).

The alternator open-circuit saturation curve and the shunt field regulator control curve intersect at approximately 10 volts (line to neutral). For values of line voltage above this, the voltage buildup of the system will be self-sustained. The shunt field requirements at rated alternator output are less than the open-circuit value. This is due to the compounding effect produced by the series field controller.

Series Field Controller

The series field controller supplies alternator excitation in proportion to alternator line current (ref. 8). The field current is derived from the rectified output of the current transformers inserted on the alternator lines. The input-output current ratio of the controller is a constant equal to 40:3.7, barring saturation of the current transformers. An output capacitor is provided to minimize the field voltage excursions that would occur as a result of load transients on the alternator.

The series field controller can magnetically deliver 800 watts. The output of the controller during a three-per-unit line fault is approximately 375 watts. At one-per-unit line current, the output is approximately 34 watts. The losses within the series field controller have been computed at 10 watts for a line current of 1 per unit having no distortion. The series controller efficiency, therefore, is approximately 77 percent. Any output of the controller in excess of rated (34 W) is time-limited. This controller characteristic is compatible with that of the alternator.

The series field controller control characteristic, as shown in figure 4, illustrates the level of excitation supplied to the alternator for various values of line current. Two items are significant. First, the controller output current exceeds the alternator field

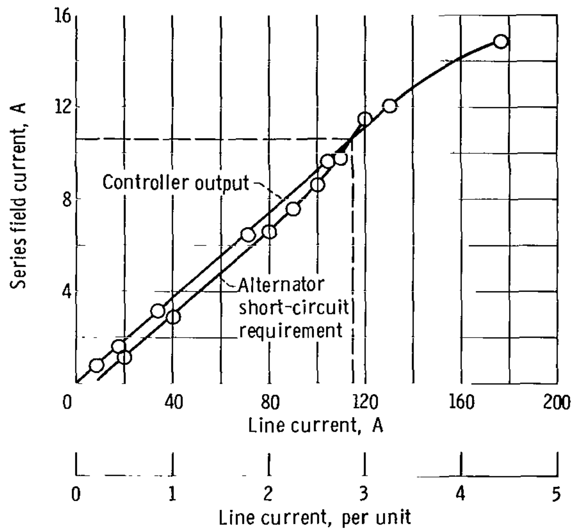


Figure 4. - Series field controller and alternator characteristics. Resistance series field, 4.40 ohms at 177° C.

requirement for all values of line current up to the level of fault current desired. The magnitude of fault current the power system will deliver corresponds to the point of intersection between the series field controller characteristic curve and the short-circuit curve of the alternator, as shown. The second significant item is that the point of intersection does occur at the level of line current required. In this system, the required fault current is approximately 3 per unit, or 120 amperes. The figure indicates that a fault current of approximately 116 amperes will be obtained.

Speed Controller

The speed controller, as illustrated in the block diagram of figure 5, applies load to the alternator as a function of the input line frequency. The controller consists of

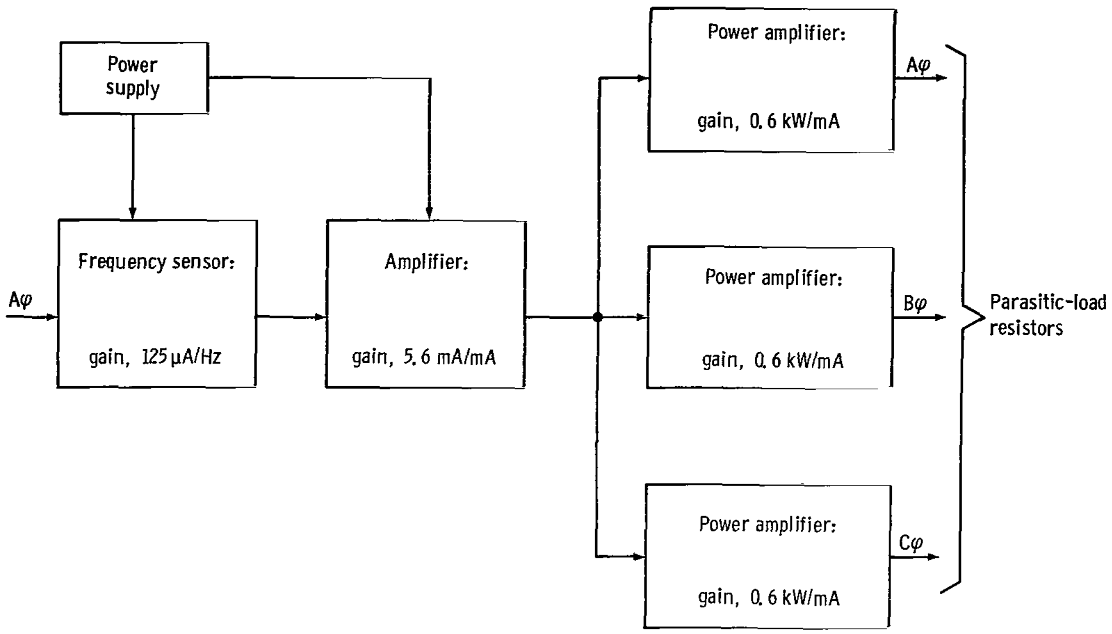


Figure 5. - Block diagram of speed controller (one channel).

three identical units (channels) which are sequentially tuned such that the turnon of the succeeding channel occurs after the preceding channel is full on. The individual channels of the speed controller have subcircuits consisting of a frequency sensor, an amplifier, and three single-phase power amplifier (output) stages.

The sensing circuits in the speed controller provide a dc output signal which is proportional to the deviation of the input frequency from a set frequency value. A frequency adjusting potentiometer in the sensing circuit permits the nulling of the circuit at the set frequency. The gain of the sensing circuit was computed to be 125 microamperes per hertz change in input frequency (ref. 8).

The output of the frequency sensing stage provides control current for a two-stage magnetic amplifier. The gain of the first-stage amplifier was computed to be approximately 700 milliamperes per milliampere of input control current. The second-stage amplifier has a potentiometer incorporated into the feedback network for the purpose of providing an adjustment of steady-state gain.

If the speed controller gain is set to obtain a parasitic power output of 6 kilowatts for a 14-hertz frequency change, the gain of the second amplifier stage will be 0.008 milliampere per milliampere change in input current. This amplifier provides impedance matching between the first amplifier stage and the power amplifier. The overall gain for the amplifier, therefore, is 5.6 milliamperes per milliampere.

The amplifier provides control current for the three single-phase power amplifier (output) stages. The power amplifier stage utilizes saturable reactors to provide a phase-controlled firing sequence for the silicon controlled rectifiers (SCR's) (ref. 8). The use of phase-controlled SCR's in the power amplifier output stage generates discontinuous line currents within the alternator. This type of current flow distorts the alternator terminal voltage (ref. 9). The amount of distortion is related to the level of current being switched. The distortion levels are minimized by the use of multiple speed control channels.

The power amplifier stage, which includes the firing circuit, has a gain of approximately 0.6 kilowatt per milliampere change in control input. The average gain of the complete speed control is 0.42 kilowatt per hertz at the design point of 6 kilowatts parasitic power for a 14-hertz change in input frequency. The maximum permissible gain for the Brayton system has been computed at 31.5 kilowatts for 1 percent of speed error (ref. 8), or 2.6 kilowatts per hertz change of input frequency. The maximum permissible gain is defined as that gain above which the system goes into continuous oscillation (limit cycle).

Figure 6 illustrates the effect of sequential tuning of the individual speed control channels. The slope of the control characteristic is a function of the gain setting and the overlap in the tuning of the individual frequency transducers. Regions of high incremental gain are shown on the figure. The maximum incremental gain for the integrated Brayton system utilizing a three-channel speed control was 0.8 kilowatt per hertz. The data for figure 6 were obtained at reduced power levels.

The power loss in each individual speed controller, including the parasitic-load resistor, at minimum condition (minimum parasitic power) was computed to be 21 watts. The power loss in each controller at full load (maximum parasitic power) was computed

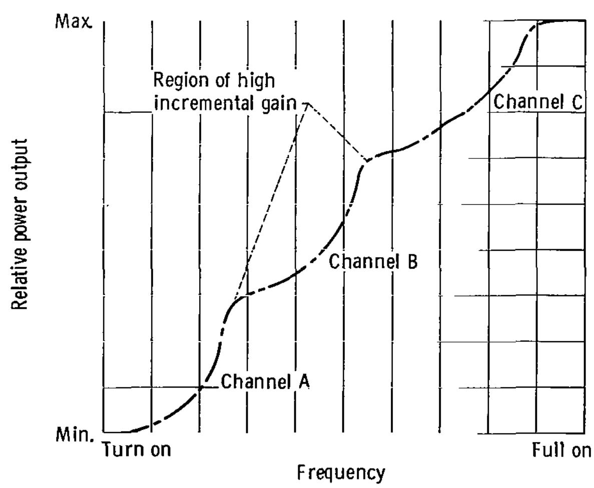


Figure 6. - Speed controller power output as function of line frequency. Parasitic-load resistance, 100 ohms.

to be 88 watts. This represents an efficiency of 99.6 percent at minimum parasitic power and 98.6 percent at maximum parasitic power based on a 6-kilowatt speed controller channel rating.

Figure 7 illustrates the effect on the speed controller control characteristic of operating over a wide frequency range and a wide voltage range. The speed controller has the desired frequency characteristic at rated input voltage (120 V). As the input voltage is reduced to 80 volts, the frequency characteristic is generally unchanged. However, the active control range has increased and the output power has begun to turn off at the high-frequency end. At 120 volts input, the speed controller output begins to turn on at very low frequencies. The low-frequency turnon occurred for frequencies below 650 hertz, and the high-frequency turnoff occurred for frequencies above 1650 hertz. The speed controller was tested over a wide range of input frequencies and line voltages to determine the effect on controller performance (1) of a change in useful system load and (2) of a startup of the integrated Brayton system. The data for figure 7 were obtained at reduced power levels.

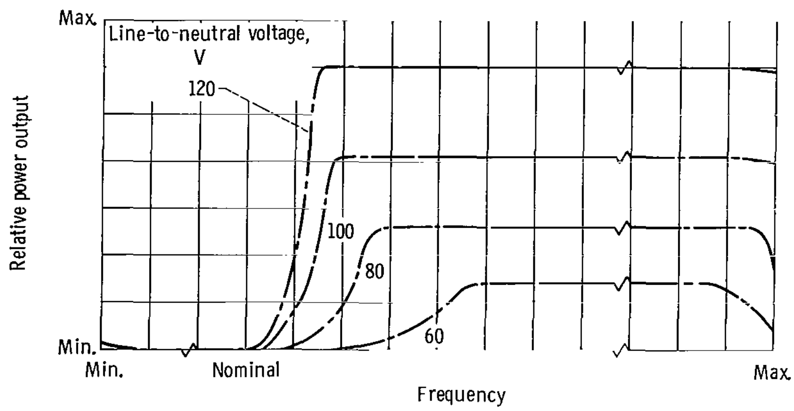


Figure 7. - Effect of line-to-neutral voltage variation on operating range of speed controller. Parasitic-load resistance, 100 ohms.

Control Component Power Losses

The control component power losses, as discussed previously, are itemized in table II. These power losses represent the difference between the power available at the useful-load bus and that developed by the alternator in this test program. The significance of the information presented is that the voltage regulator and the speed controller utilize approximately 1 percent of the alternator output. The power losses as shown in table II represent those losses incurred at a useful load of 10 kilowatts.

TABLE II. - CONTROL COMPONENT

POWER LOSSES

	Power losses, W	Percent of system rating
Voltage regulator shunt field	41	0.38
Voltage regulator series field	10	.09
Speed controller (three units)	63	.59
Total	114 W	1.06 percent

APPARATUS

A block diagram of the system tested is shown in figure 8. Instrumentation points are shown on the figure. The instrumentation in the test facility provided the capability for measuring: (1) useful-load voltage, (2) line frequency, (3) line current, (4) useful-load power output, and (5) field currents. The specifications for the instruments are listed in table III.

The major components in the test facility are the air turbine, the prototype (research) alternator, and the electrical control package (ECP). The ECP was designed to operate in a vacuum environment (ref. 11). Cooling is provided by a cold plate. For the tests performed, the coolant was water, which could be heated by means of an immersion heater. The drive for the research alternator was a commercial turbine designed to operate on air and to produce 16 horsepower (11.9 kW) at 36 000 rpm.

The polar moment of inertia of the turbine and research alternator combination is 0.039 in.-lb/sec^2 (4.4×10^{-3} kg-m^2). The Brayton turbine-alternator-compressor package has a polar moment of inertia of 0.058 in.-lb/sec^2 (6.5×10^{-3} kg-m^2). The difference in inertias did not affect the results of the steady-state tests.

The test facility is shown in figure 9. The alternator is at the upper right. The facility turbine is in the upper center section. The electrical power connections for the alternator, as well as those connections for the coolant and for bearing lubrication, are visible. The ECP is in the foreground, together with the facility water-cooled cold plate.

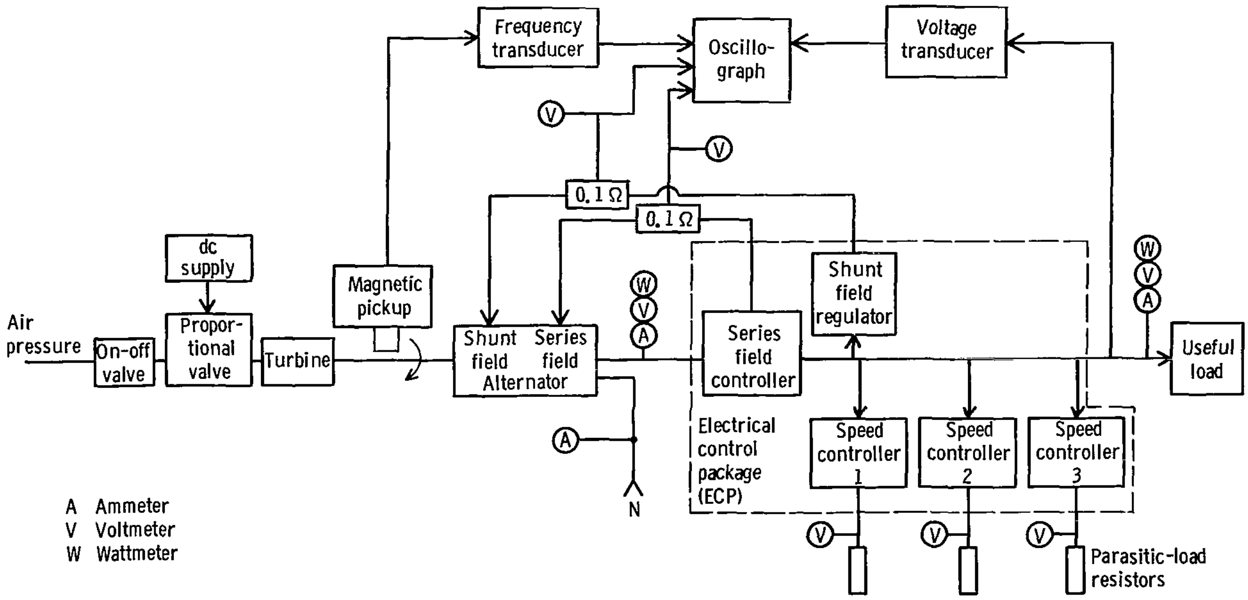


Figure 8. - Apparatus and instrumentation.

TABLE III. - INSTRUMENT SPECIFICATIONS

Instrument	Use	Range	Accuracy	Additional specifications
True rms voltmeter	Line voltage	0 to 150 V	0.25 Percent of full scale	Accuracy: to 2500 Hz
Wattmeter	Power	Nominal input: 100 V; 5 A	1 Percent of full scale	Accuracy: dc to 2500 Hz
Current trans-former	Line currents	Current ratio: 50/5 A	±0.1 Percent of ratio	Accuracy: 70 to 2500 Hz; capacity; 25 V-A
Shunt	Secondary of current transformer, field currents	Resistance: 0.1 Ω	0.04 Percent (in air)	Capacity: 15 A
True rms to dc con-verter	rms voltage on shunts	Input: 0 to 1 V Output: 0 to 10 V	0.1 Percent of full scale	Accuracy: 40 to 3×10^4 Hz
Integrating digital voltmeter	Output of true rms to dc converter	0 to 15 V	0.1 Percent ±1 digit	----------------------
dc milli-voltmeter	Voltage of field current shunts	$\left\{\begin{matrix}\text{0 to 200 mV}\\\text{0 to 400 mV}\end{matrix}\right\}$	0.25 Percent of full scale	----------------------
Oscilloscope	Peak line voltage	100 V/cm	Deflection: 3 percent	----------------------
Temperature re-corder	ECP cold-plate temperature	200 to 650 K	±1 K	----------------------
Counter	Line frequency	0 to 9999.9 Hz	±0.1 Hz	----------------------

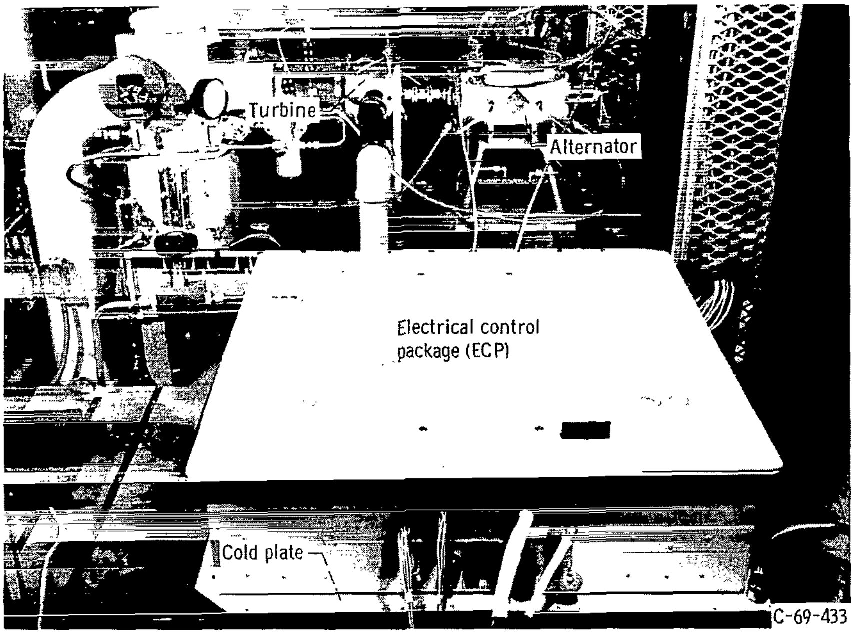


Figure 9. - Test facility for 1200-hertz electrical subsystem.

The useful and parasitic load banks are not shown. The useful (vehicle) load rating of the system is 10 kilowatts, 0.85 (lagging) power factor.

RESULTS AND DISCUSSION

The steady-state performance characteristics of the prototype (research) alternator, voltage regulator, and speed controller are presented in this section. In this test program an air-turbine was used as the power source. Transient performance tests on this test facility are reported separately (ref. 6).

Load Effects on Line Frequency

The control of alternator frequency (speed) as provided by the speed controller is illustrated in figure 10. Tests were conducted over a range of useful loads from 0 to 10 kilowatts at power factors of 1.0 and 0.85 (lagging). The figure indicates that a 25-hertz control range is obtained for this test. The 25-hertz control range represents a speed regulation of approximately 2 percent (2.07). The total power in the useful and parasitic loads (including control losses) must be equal to the alternator power. In this test program the alternator power is a constant equal to 10.7 kilowatts.

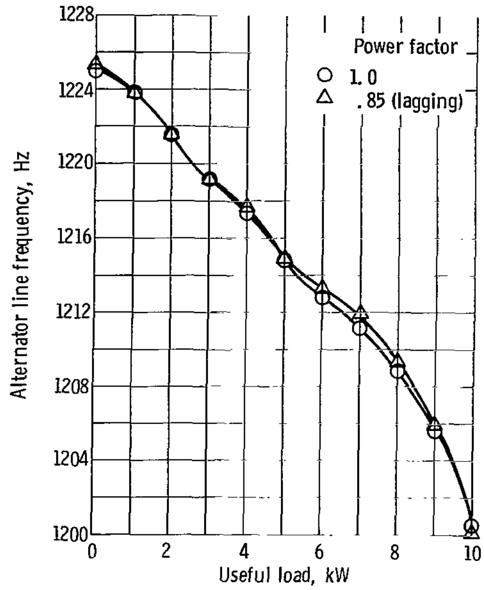


Figure 10. - Alternator frequency against useful load for 10.7-kilowatt total alternator output at 1.0 and 0.85 (lagging) useful-load power factor.

At zero useful load, the line frequency for the two power factor loads of 1.0 and 0.85 (lagging) has an offset equal to 0.2 hertz. This offset normally should not exist. The source of this offset creates an offset in line voltage, in alternator power factor, and in alternator neutral current. The offset can be attributed to changes in the cold-plate temperature of the packaged controls, and to the difficulty of maintaining the alternator output power at 10.7 kilowatts. The alternator power for each load point was maintained within 0.1 kilowatt of the 10.7 kilowatts desired output. Based on figure 10, the change in line frequency for a 10-kilowatt useful-load change is 25/10 or 2.5 hertz per kilowatt. Assuming a linear speed control characteristic, the tolerance on the alternator power setting of ±0.1 kilowatt could generate a frequency change of ±0.2 hertz.

The cold-plate temperature increased prior to the start of the 0.85-power-factor (lagging) test run. The temperature increase, as recorded, amounted to approximately 2.5° C. Subsequently, a heat run was performed on the electrical controls. Table IV illustrates the effect of cold-plate temperature on the operating frequency and the line voltage for the test system. For a 33° C increase in the cold-plate temperature (from 22° to 55° C), the operating frequency increased by 3.6 hertz (1200.2 to 1203.8 Hz, or ~0.3 percent).

Assuming a linear characteristic of frequency as a function of temperature, the 2.5° C increase in cold-plate temperature, as recorded at the start of the 0.85-power-factor (lagging) test run, would constitute a 0.27-hertz increase in frequency. There-

TABLE IV. - EFFECT OF TEMPERATURE ON OPERATING FREQUENCY AND VOLTAGE

[Useful load, 10 kW (0.85 power factor (lagging)); total alternator load, 10.7 kW.]

Temperature of cold plate, °C	Temperature of cold plate, °F	Operating frequency, Hz	Average line voltage, V
22	72	1200.2	120.1
30	86	1201.6	119.8
43	109	1202.9	119.9
55	131	1203.8	119.8

fore, both the change in cold-plate temperature and the tolerance in maintaining an alternator power output of 10.7 kilowatts contributed to the shift in operating frequency during the course of the test program.

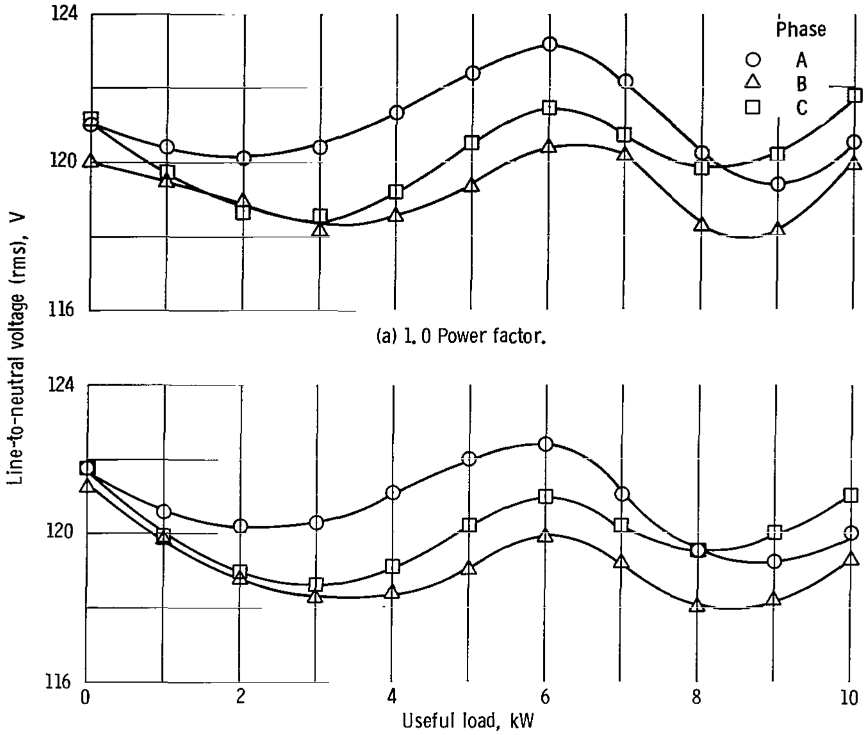
Table IV also indicates a change in the line voltage occurred during the heat run. The average line voltage decreased by 0.3 volt (120.1 to 119.8 V).

Load Effects on Line Voltage

The alternator rms phase voltages are plotted as a function of useful load, as illustrated in figure 11 for useful-load power factors of 1.0 and 0.85 (lagging). For useful loads below 8 kilowatts, the voltage on phase A was the highest. The voltage on phase B was the lowest for all loads and power factors. This voltage difference between phases is a function of alternator voltage balance and speed control phase balance. Balanced load impedances were used for both the useful and parasitic outputs. The result of the alternator performance tests indicated the phase B rms voltage was consistently 1 volt below phase A and C (ref. 10).

The unbalance in the speed controller output voltage occurs because the output stages have different conduction angles. This difference in conduction angle is the result of component variations within each output stage.

The variation in the magnitude of the phase voltage as a function of useful load is also illustrated in figure 11. The voltage variation is due to a control interaction between the shunt field regulator sensing circuit and the speed control power amplifier



(b) 0.85 Power factor (lagging).

Figure 11. - Alternator phase voltages as function of useful load for 10.7 kilowatts total alternator output.

(output) stages. The use of phase-controlled SCR power amplifier stages in the speed controller distorts the line voltage at the instant of SCR turnon. The distortion level is a function of the number of speed control channels in the electrical subsystem and varies with the conduction angle of each channel.

The sensing circuit of the shunt field regulator senses the average value of the peak of the line voltages. As a result, the regulator cannot maintain the line voltage at a constant rms value because of this voltage distortion as produced by the speed controller. For 1.0-power-factor useful loads between 0 and 10 kilowatts, the phase voltages range from 123.2 to 118.0 volts (rms). For 0.85-power-factor (lagging) useful loads between 0 and 10 kilowatts, the phase voltages ranged from 122.4 to 118.0 volts.

In figure 12, the alternator line voltages are plotted as a function of alternator load. The speed control was not connected to the system. The variations in line voltage as discussed in the preceding paragraph did not take place. The line voltage did rise gradually (~1.0 V) with an increase in alternator load. This occurred because the alternator was overcompounded, which was caused by the series field controller.

The crest factor varied from 1.5 to 1.24 for useful loads ranging from 0 to 10 kilowatts at 1.0 and 0.85 (lagging) power factor. The crest factor of any waveshape is the

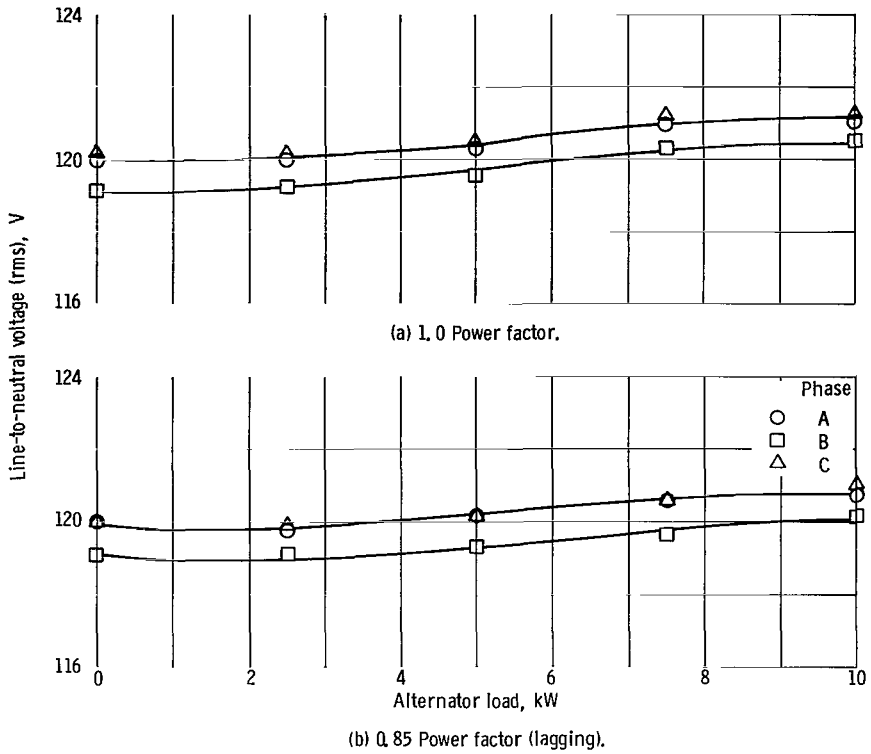


Figure 12. - Alternator phase voltages as function of alternator load.

ratio of the peak voltage to the rms voltage. For a nondistorted sine wave, the crest factor is a constant equal to $\sqrt{2}$. Voltage distortion is generated, as previously discussed, by the speed controllers. The resulting effect of the speed controllers on the crest factor is plotted in figure 13. The variation in crest factor is generated because the speed controller power amplifier stages have a maximum conduction angle of approximately 170° and because the succeeding speed controller channel is normally tuned to deliver approximately 500 watts at the turnon frequency, as illustrated in figure 6. These effects are in addition to the effect on crest factor produced by the change in the power amplifier conduction angle.

The voltage variation on alternator phase A is also plotted in figure 13. The crest factor was determined from the phase A voltage. The significant fact is that the minimum crest factor occurred at approximately the maximum value of rms line voltage. This relation would be expected in any test system which uses a peak sensing voltage regulator where voltage distortion is present. In figure 14, the effect of the speed controller power amplifier stages on both the useful-load voltage and the alternator line current is illustrated at various useful loads.

The waveshapes for the 10-kilowatt useful load were used as a reference. The speed

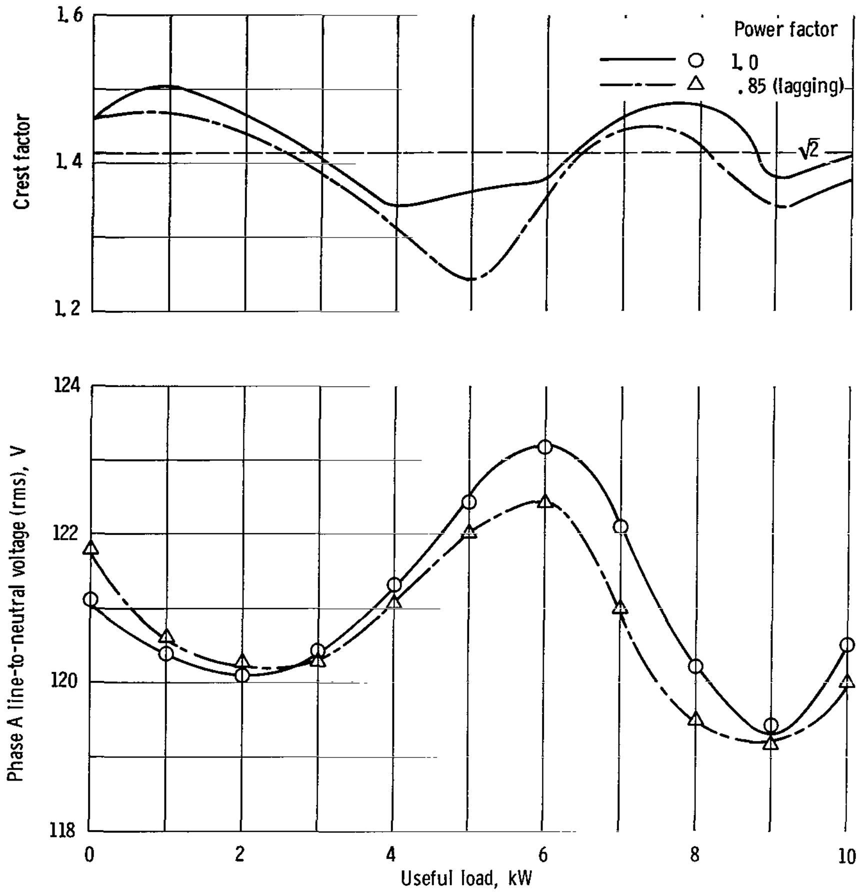
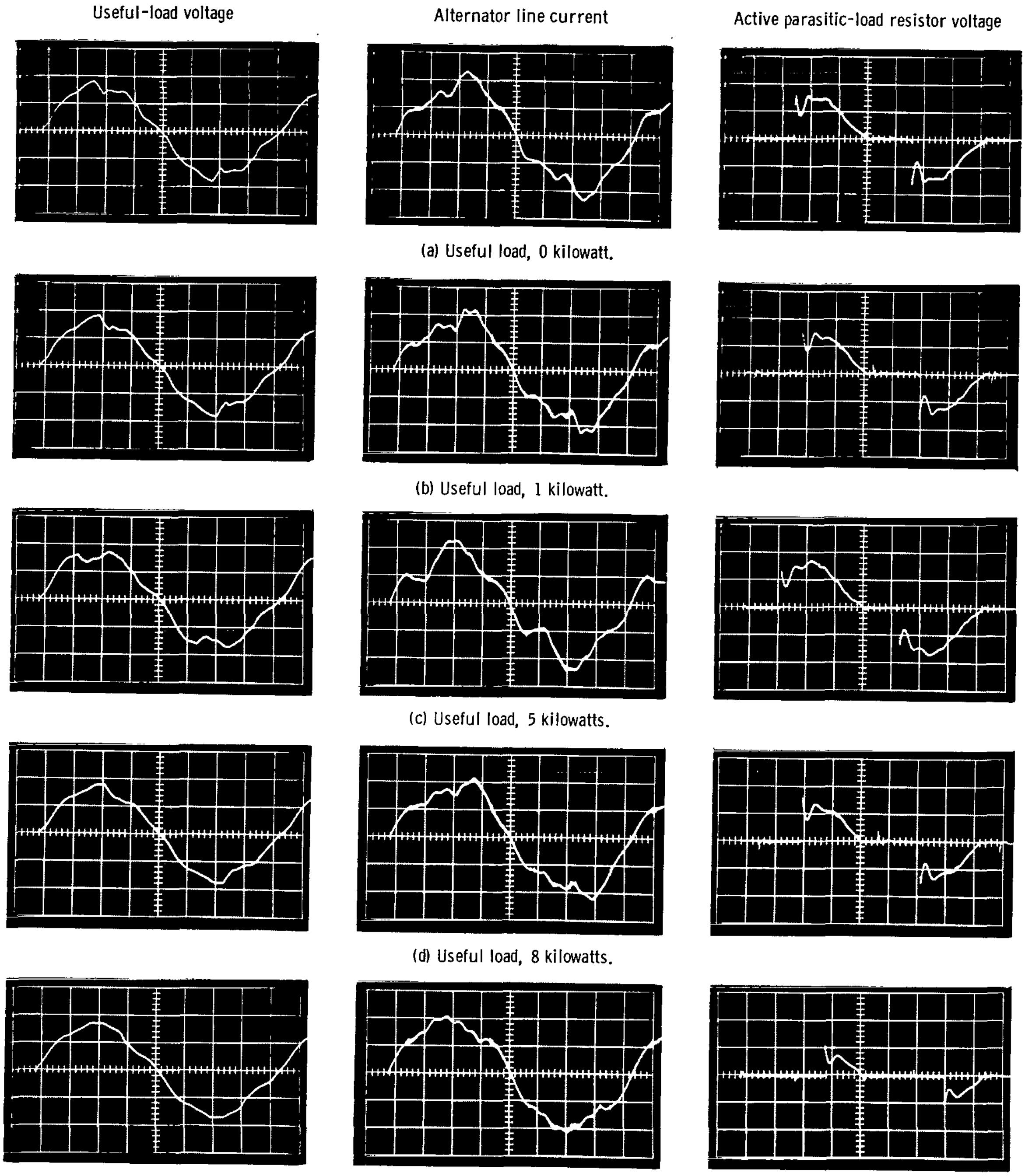


Figure 13. - Crest factor and phase A line voltage as function of useful load at 1.0 and 0.85 (lagging) power factor for 10.7-kilowatt total alternator load.

controller at this useful load has the minimum conduction and therefore the minimum effect. The remaining load points were selected to depict the worst case of voltage distortion at the useful-load terminals. Unity-power-factor load voltages are shown in this figure. All waveshapes were recorded on phase A, which was an arbitrary choice.

In addition, the voltage at the active parasitic-load resistor is shown. The reference to active parasitic load refers to the particular speed control unit whose conduction angle was directly affected by any incremental change in line frequency. For example, in figures 14(a) and (b) the second unit was actively controlling the alternator speed; the first unit was full on. In figures 14(c) to (e), the first unit was actively controlling the alternator speed; the second unit was full off. A comparison of the useful-load voltage and alternator line current with the parasitic-load voltage waveshapes for each useful load illustrates the interrelation between the speed control conduction angle and the voltage distortion. Voltage distortion appears as a notch in the voltage waveshape. At a particular useful load, the notch will appear at the 90° location in the voltage waveshape. At



(a) Useful load, 0 kilowatt.

(b) Useful load, 1 kilowatt.

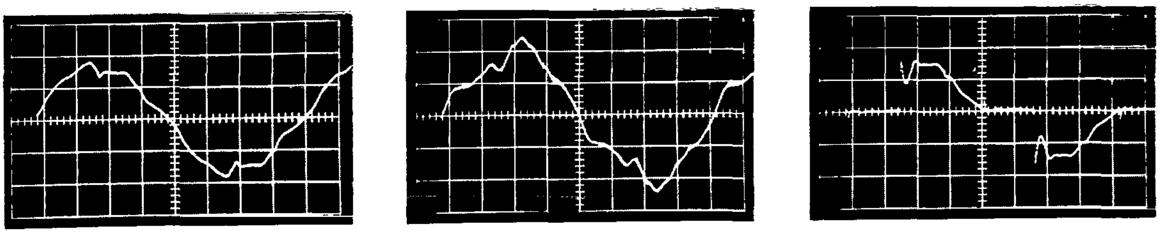
(c) Useful load, 5 kilowatts.

(d) Useful load, 8 kilowatts.

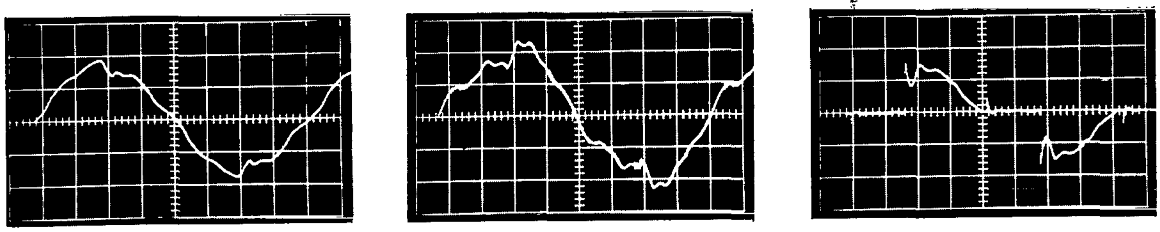
(e) Useful load, 10 kilowatts.

Figure 14. - System characteristics as function of useful load at 1.0 power factor with 10.7-kilowatt total alternator load.

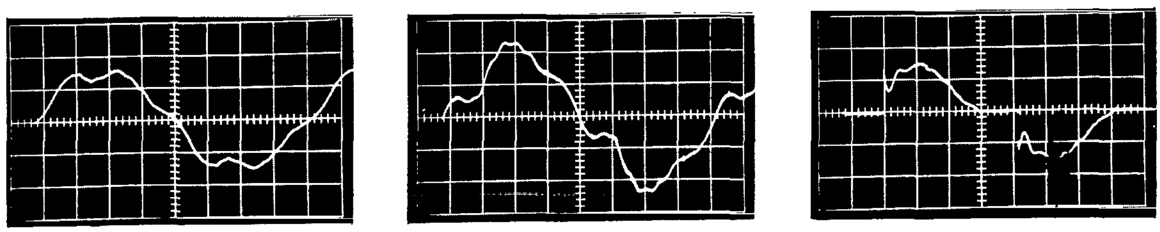
Useful-load voltage | Alternator line current | Active parasitic-load resistor voltage



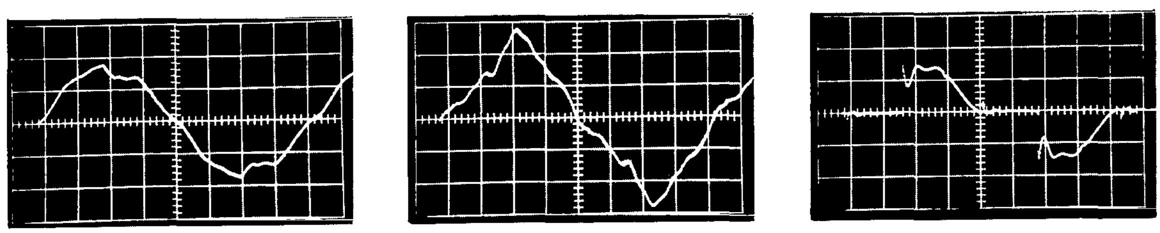
(a) Useful load, 0 kilowatt.



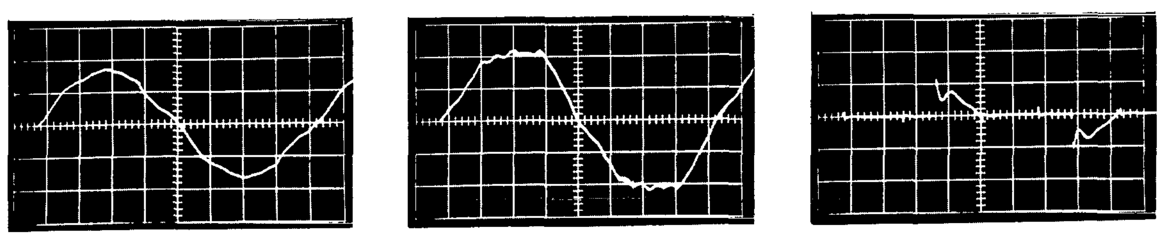
(b) Useful load, 1 kilowatt.



(c) Useful load, 5 kilowatts.



(d) Useful load, 7 kilowatts.



(e) Useful load, 10 kilowatts.

Figure 15. - System characteristics as function of useful load at 0.85 power factor (lagging) with 10.7-kilowatt total alternator load.

this angle the crest factor, as discussed previously, is adversely affected.

The parasitic-load-resistor voltage waveshape has two noticeable characteristics. One is the abrupt change (high dv/dt) in voltage, as is characteristic of an SCR turnon. The second is the transient reduction in voltage occurring immediately after SCR turnon. An analog computer study was initiated to verify the cause of this phenomenon. Basically, the cause was reduced to an interaction between the alternator winding (phase) inductance and the LC filter in the speed controller. A detailed discussion of the results of this study, including the procedure followed, is presented in an unpublished report by Richard C. Bainbridge of Lewis.

Figure 15 illustrates the effect of the speed controller power amplifier (output) stages on both the useful-load voltage and the alternator line current. The load conditions for this figure are the same as those of figure 14, except the useful-load power factor is now 0.85. The useful-load values representing the highest levels of distortion are generally the same for each of the two useful-load power factors.

The voltage modulation present at the useful-load terminals of the electrical subsystem is illustrated in table V. Voltage modulation is defined by the equation

$$\mathrm{VM(percent)} = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \times 100$$

where E is the rms value of the line voltage. The modulation data were derived by means of a strip-chart recorder. The level of modulation is affected by the voltage regulator - speed control interaction. This is evident since the minimum level of voltage modulation occurs when the parasitic power is at a minimum, nominally 0.7 kilowatt. The highest level of modulation was 0.63 percent, which occurred at 5 kilowatts useful load. The minimum modulation level, which occurred at full 10 kilowatts useful load (0.7-kW parasitic load), was 0.33 percent.

TABLE V. - VOLTAGE AMPLITUDE MODULATION

Useful load (1.0 power factor), kW	Voltage modulation, percent
0	0.46
5	.63
10	.33

Alternator Neutral Current

Figure 16 illustrates the magnitude of the alternator neutral current generated in this electrical subsystem. The existence of the neutral current is the result of the inherent characteristics of the alternator, the voltage regulator, and the speed controller. The specific component characteristics which affect the magnitude of neutral current are (1) line voltage unbalance, (2) load impedance unbalance, (3) line voltage distortion, (4) speed controller conduction angle, (5) overlap of the speed controller channels, and (6) speed controller output power unbalance.

The unbalance in line voltage as previously discussed and shown in figure 11 amounts to about 3 volts maximum. The magnitude of this unbalance varies with useful load. The useful-load bank for the system was a commercial three-phase-ganged unit having a load unbalance of 2 percent maximum. The parasitic-load bank consisted of resistive elements having a tolerance of plus 0 percent, minus 10 percent. The amount of line voltage distortion, as discussed in figure 13, is a function of the speed controller power amplifier stages. At a 90° conduction angle (~1-kW useful load), an instantaneous

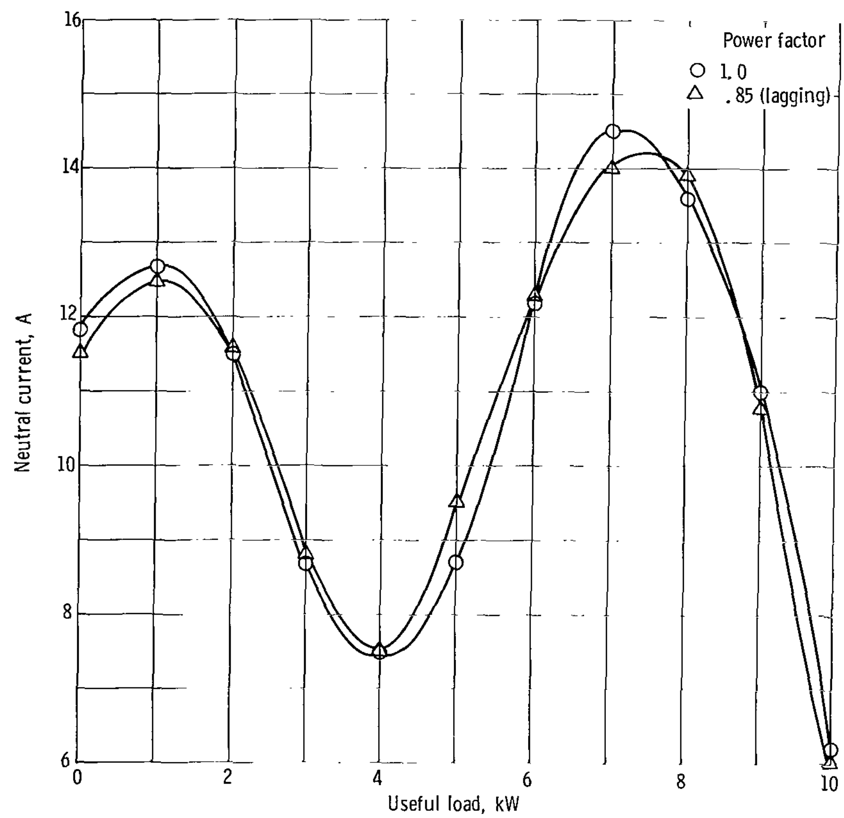


Figure 16. - Alternator neutral current as function of useful load at 1.0 and 0.85 (lagging) power factor for 10.7-kilowatt total alternator load.

40-volt change in line voltage is experienced, as shown in figures 14 and 15. This voltage change would occur every 120° for a fixed useful load.

At conduction angles of less than 60°, all the line current for each speed controller channel will flow through the neutral wire. The frequency of the neutral current is three times the line frequency and the magnitude of the current is $\sqrt{3}$ times the line current. Above 60° conduction, some of the line current will flow between phases in addition to the neutral. A full 180° of conduction is a prerequisite to the elimination of current flow in the neutral.

The overlap or tuning of the individual speed control channels affect the peak magnitude of neutral current as well as the line frequency at which the peak occurs. As the succeeding channels begin to apply parasitic load, the neutral current of that channel will add to the neutral current produced by the preceding speed control channel. The turnon frequency of the individual channels is adjustable, and is normally set to provide maximum power output linearity for the desired speed controller gain. The turnon frequencies of the individual channels are set nominally in 14-hertz increments. The parasitic power at the turnon frequency is nominally 500 watts.

The total neutral current in the system is not the sum of the currents previously itemized. Some of the neutral currents will flow continuously while others are intermittent, depending on speed controller conduction angle and line frequency. The range of neutral currents as shown in figure 16 was from 6 to 14.5 amperes.

The neutral current peaks at useful loads of approximately 1 and 7 kilowatts. A 1-kilowatt useful load represents a speed controller conduction angle of approximately 90° (98° actual) in the second channel. A 7-kilowatt useful load represents the same conduction angle of approximately 90° in the first channel. The minimum neutral current, at 10 kilowatts useful load, is 6.2 amperes. Since the power delivered by the alternator is a constant equal to 10.7 kilowatts, the first speed control channel for a 10-kilowatt useful load has a conduction angle of less than 60°. This is shown in figures 14 and 15. The minimum neutral current generated is therefore due to a combination of component unbalances and low speed controller conduction angles.

Alternator Load Unbalance

Several of the component characteristics which generate neutral currents also contribute to an unbalance in alternator phase load. Load unbalance is defined as the difference between the highest and lowest phase load on the alternator. Specifically, these characteristics are (1) line voltage unbalance, (2) load impedance unbalance, (3) line voltage distortion, and (4) speed controller output power unbalance. Figure 17 illustrates the alternator load unbalance as a function of useful load.

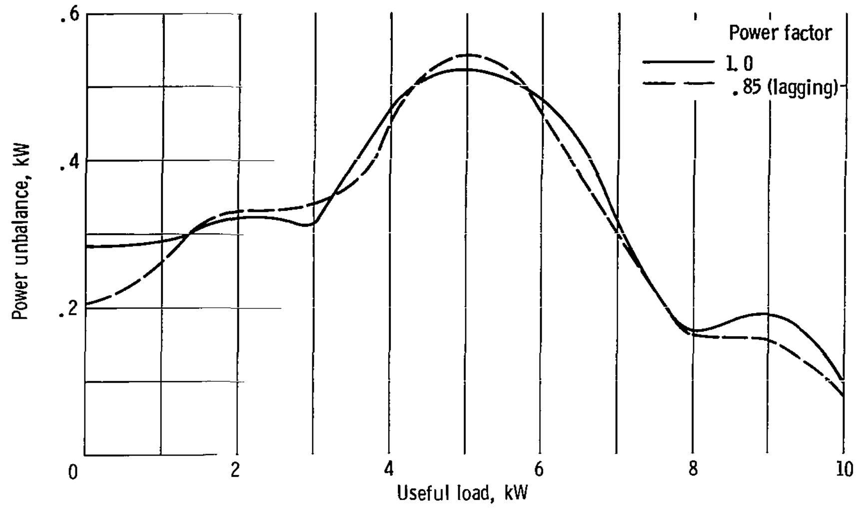


Figure 17. - Alternator phase power unbalance as function of useful load at 1.0 and 0.85 (lagging) power factor for 10.7-kilowatt total alternator power.

An unbalance could represent an overload on the alternator armature. It is therefore significant that at the maximum useful load of 10 kilowatts, the unbalance be sufficiently low to maintain the temperature of the alternator winding to a safe value. The maximum unbalance at 10 kilowatts useful load is 100 watts, or approximately 3 percent of the alternator phase power rating. The peak unbalance coincides with the turnon of the second speed controller channel. At this point, the unbalance of the first channel, which is at a maximum conduction angle, adds to the unbalance of the second channel. The maximum power unbalance is 540 watts. This peak unbalance occurs at a 5-kilowatt, 0.85-power-factor useful load.

Alternator Power Factor

The total power factor as seen by the alternator is plotted in figure 18 as a function of useful load. The magnitude of the useful load ranged from 0 to 10 kilowatts at 1.0 and 0.85 (lagging) useful-load power factors. The alternator power factor is a function of the various loads on the alternator. The alternator loads consist of (1) the useful load bank, (2) the phase-controlled speed controller, including the inductor-capacitor (LC) input filter, and (3) the voltage regulator.

At zero useful load, the speed controller has maximum power output. As shown in figure 18, the alternator power factor at zero useful load is 0.99 and 0.98 for the 1.0- and 0.85-power-factor curves, respectively. These values of alternator power factor should be identical. It was found that the discrepancy was caused by a change in cold-

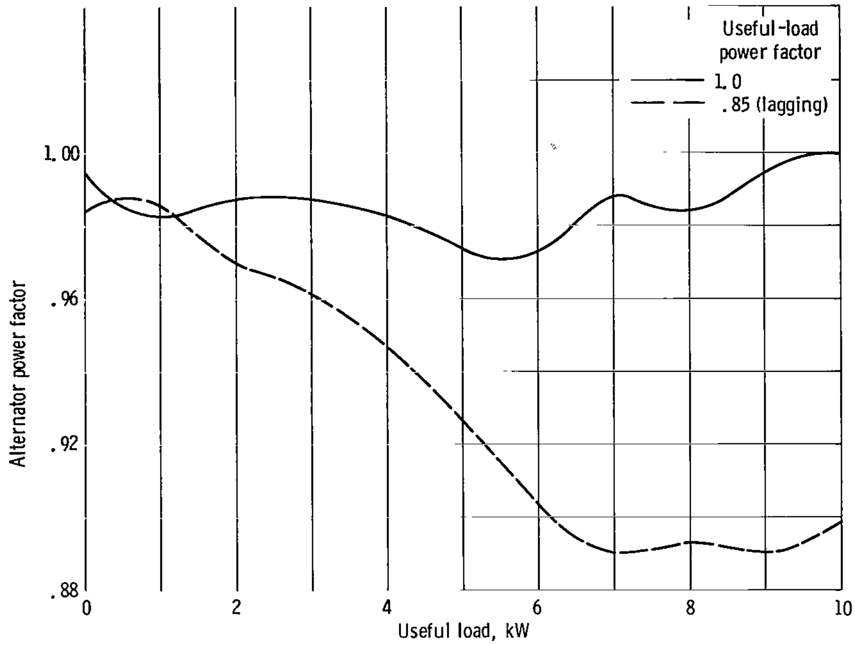


Figure 18. - Alternator power factor as function of useful load at 1.0 and 0.85 (lagging) power factor for 10.7-kilowatt total alternator load.

plate temperature for the packaged controls. The lowest power factor which was seen by the alternator over the range of 0.85-power-factor useful loads was 0.89. The lowest alternator power factor over the range of 1.0-power-factor useful loads was 0.97.

In figure 19, the series field current is plotted as a function of useful load over a range of 0 to 10 kilowatts at 1.0 and 0.85 (lagging) power factor. The series field current is determined by the line current which is a function of (1) the alternator line voltage and (2) the alternator power factor.

In this system, the average value of the alternator line voltages vary with useful load, as also shown in figure 19. This variation in line voltage is due to the voltage distortion in the electrical subsystem, as previously discussed in connection with figure 11. The alternator power factor, as previously discussed in connection with figure 18 is a function of both the useful load and the speed controller. The maximum value of series field current was 2.82 amperes at a useful load of 6 kilowatts, 1.0 power factor. For 0.85-power-factor (lagging) useful loads, the maximum field current was 3.1 amperes at a useful load of 7 kilowatts.

The output of the shunt field regulator for useful loads of 0 to 10 kilowatts at 1.0 and 0.85 (lagging) useful-load power factors is also shown in figure 19. The shunt field regulator supplies the difference in field current between that required to maintain the desired line voltage and that supplied by the series field controller.

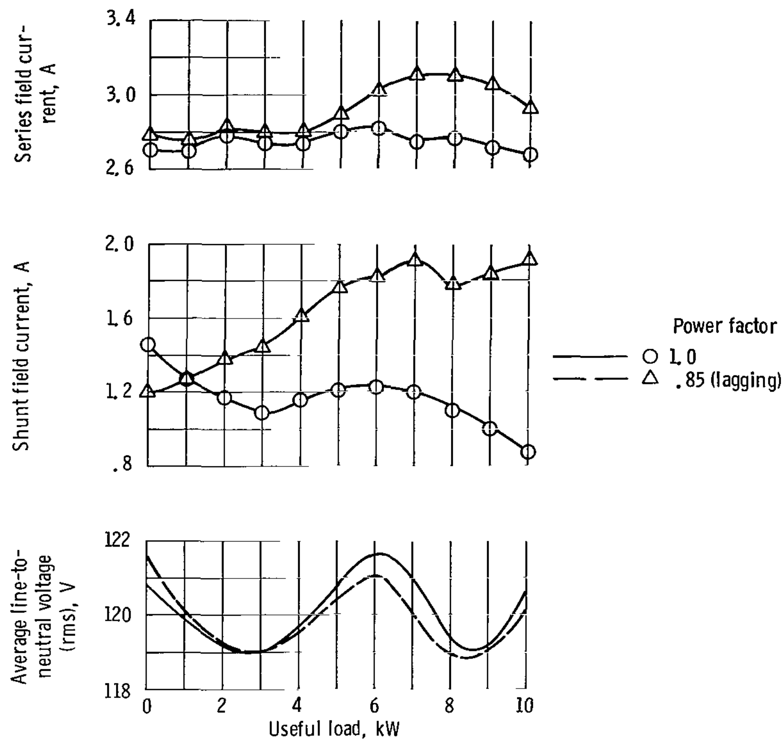


Figure 19. - Effects of voltage distortion on alternator excitation as function of useful load at 1.0 and 0.85 (lagging) useful-load power factor and 10.7-kilowatt total alternator output.

The shunt field current at zero-kilowatt useful load was different for the two useful-load power-factor tests conducted on this electrical subsystem. This discrepancy is a function of the cold-plate temperature, as discussed previously. The maximum shunt field current at 0.85-power-factor (lagging) useful load was 1.9 amperes. The useful load at this current level was 7 kilowatts. The maximum shunt field current at 1.0-power-factor useful loads was 1.45 amperes. This current level occurred at zero useful load. A secondary peak in shunt field current at 1.0-power-factor useful loads occurred at 6 kilowatts. The value of field current was 1.23 amperes.

Alternator Excitation Characteristics

The alternator field excitation is plotted in figure 20 as a function of alternator output power. The purpose of this test was to determine the characteristics of the alternator and the voltage regulator combination for a range of alternator loads. The speed controller was inhibited during this test; however, the speed controller input filter re-

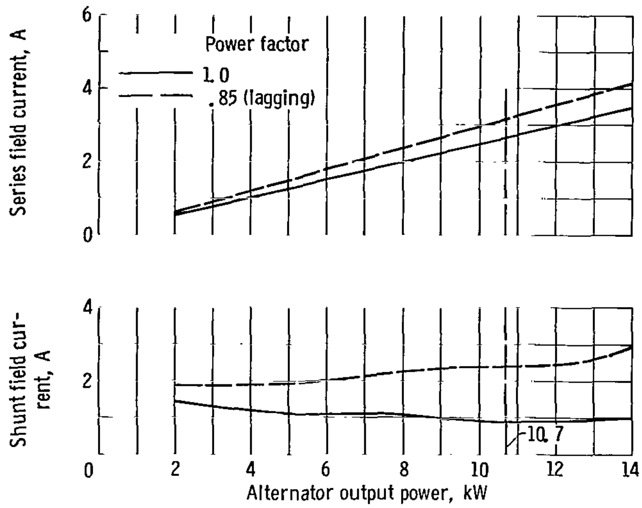


Figure 20. - Shunt field regulator and series field controller output against alternator load at 1.0 and 0.85 (lagging) power factor.

mained on the line. The alternator power output was varied from 2 to 14 kilowatts at 1.0 and 0.85 alternator power factors. All previous data presented in this report were obtained at a constant alternator output of 10.7 kilowatts, wherein the useful load was varied from 0 to 10 kilowatts for 1.0 and 0.85 (lagging) useful-load power factors.

The series field current ranged from 2.68 to 3.11 amperes, as shown in figure 19. This is the same range of series field current as illustrated in figure 20, at the 10.7-kilowatt alternator output power level. The range of shunt field current, also shown in figure 19, was from 0.88 to 1.9 amperes. This range of current was less than that illustrated in figure 20. This trend was not unexpected since the actual alternator power factor in this test was lower than in the previous tests (0.85 compared to 0.89).

SUMMARY OF RESULTS

Steady-state tests performed on the 10-kilowatt, 0.85-power-factor (lagging), 1200-hertz Brayton electrical subsystem verified the capability of the electrical components to deliver full load at the desired levels of voltage and frequency. Experimental evaluation of the subsystem produced the following results:

1. The frequency control range was 25 hertz (~2 percent) for a 10-kilowatt useful-load change at 1.0 and 0.85 (lagging) power factors.

2. The voltage regulation was 120 volts plus 3.2 volts, minus 2.0 volts for a

10-kilowatt useful-load change at 1.0 and 0.85 (lagging) power factors. A 3-volt change in line voltage, which resulted from an interaction between control components, is included in this voltage variation.

3. The range of voltage modulation varied from 0.63 to 0.33 percent for a 10-kilowatt useful-load change at 1.0 power factor.

4. The crest factor of the useful-load voltage varied from 1.5 to 1.24 for a 10-kilowatt useful-load change at 1.0 and 0.85 (lagging) power factor.

5. The flow of neutral current exists in the phase-controlled speed controller and has a maximum value of 14.5 amperes at 7 kilowatts useful load.

6. The steady-state operating frequency of the electrical subsystem is a function of base plate temperature. A change in base plate temperature from 22° to 55° C results in a 3.6-hertz (~0.3 percent) increase in operating frequency.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 9, 1970,
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